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Misalignment Induced Aberrations of JWST: Isolating Low Order Primary Figure Residuals from Misalignment

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Kevin P. Thompson, Tobias Schmid, and Jannick P. Rolland

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Presented at Mirror Technology Days, Boulder, Colorado, USA, 7-9 June 2010.

14. ABSTRACT

It is important to isolate mirror shape accuracy from misalignment to maximize the ability to correct images in the James Webb Space Telescope. In this effort, nodal aberration theory was used to characterize the misalignment-induced aberration fields. This led to the discovery of a new misalignment-induced field dependence. A methodology has also been developed to integrate as-measured mirror figure errors characterized by a Zernike polynomial fit with nodal aberration theory.

15. SUBJECT TERMS

Nodal Aberration Theory, James Webb Space Telescope, Misalignment, Segmented, Mirror, Adaptive Optics, Coma, Astigmatism, Field of View, Zernike

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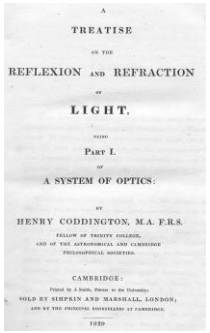
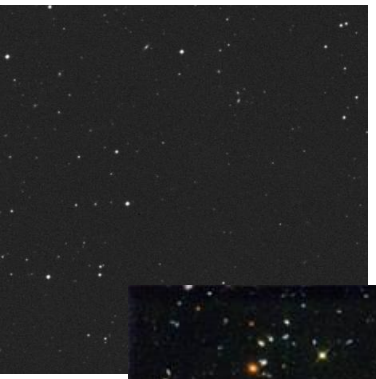
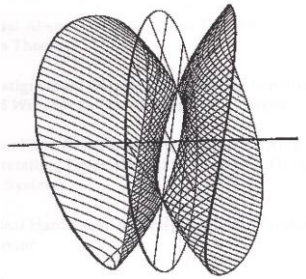
Misalignment-Induced Aberrations of JWST:

Isolating Low Order Primary Mirror Figure Residuals from Misalignment



Kevin P. Thompson/ORA
Tobias Schmid/CREOL
Jannick P. Rolland/Univ. of Rochester
kthompson@opticalres.com





NASA Mirror Tech.
Boulder, CO
June 7-9, 2010

New Results in Nodal Aberration Theory Applied to JWST

- **Recent work by the authors to apply nodal aberration theory to characterize the misalignment-induced aberration fields in astronomical telescopes has led to some important new results including**
  - **A new misalignment-induced field dependence Field-Centered, Field-Asymmetric, Field-Linear Astigmatism**
  - **A methodology has been found to integrate as-measured mirror figure error characterized by a Zernike polynomial interferogram fit with nodal aberration theory (NAT)**
- **The second result allows isolating figure error from misalignment, allowing dynamic range for correction to be conserved**

Fundamentals of Misalignment Induced Aberration Fields

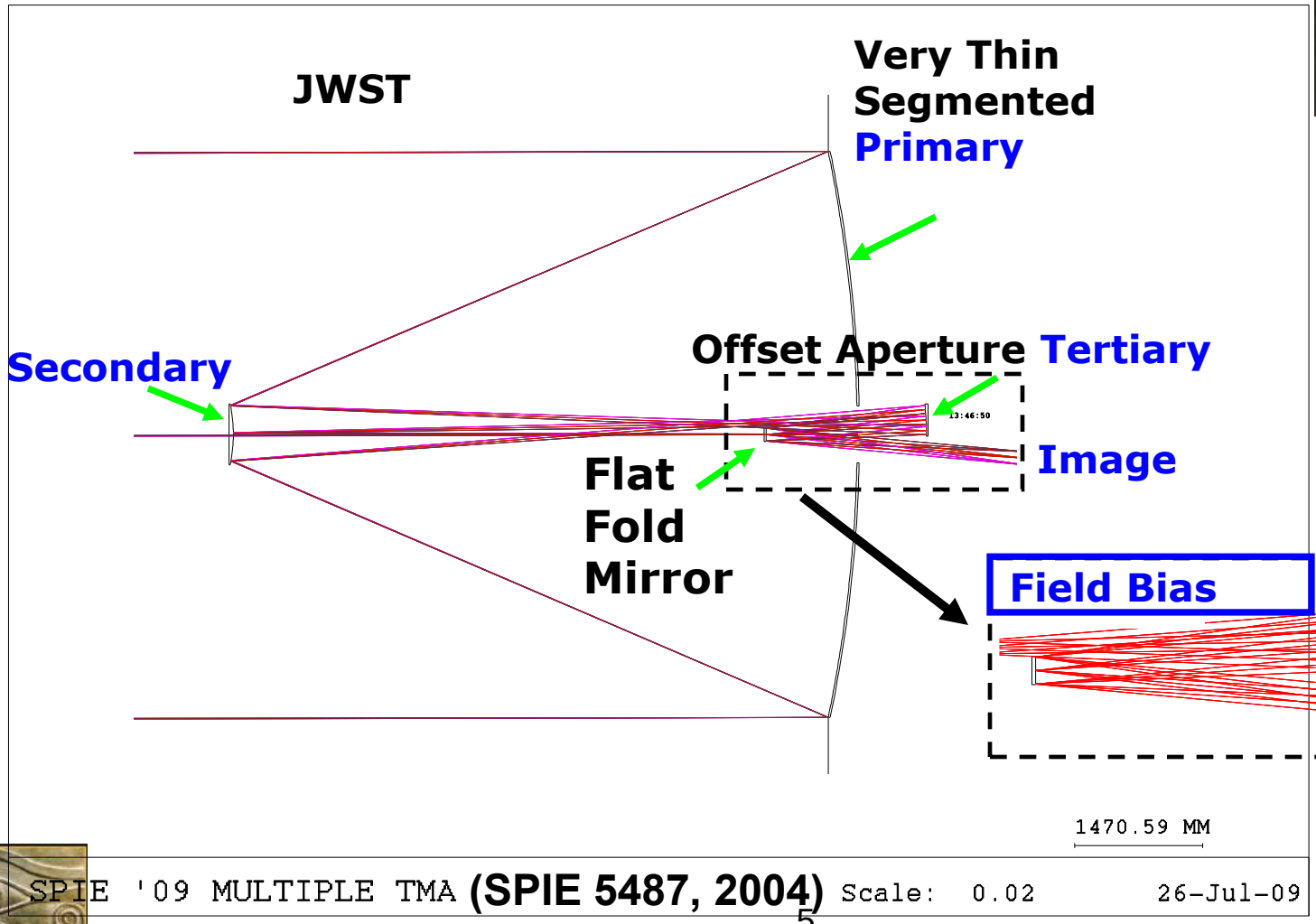
- A misaligned telescope (including TMA) has no new aberration types
- The existing aberration types often develop new field dependencies for the magnitude and orientation within the field of view
- The new field dependencies are best characterized by characteristic, intrinsic nodal geometries (aberration zero points) that are reported in K.P. Thompson, JOSA A, 2005 (3rd) and JOSA A, 2009, 2010 (5th)
- In general, once misalignment coma is removed, the remaining misalignment astigmatism is zero on-axis, but it is NOT field quadratic

K. P. Thompson, "Description of the third-order optical aberrations of near-circular pupil optical systems without symmetry," J. Opt. Soc. Am. A 22, 1389-1401 (2005).

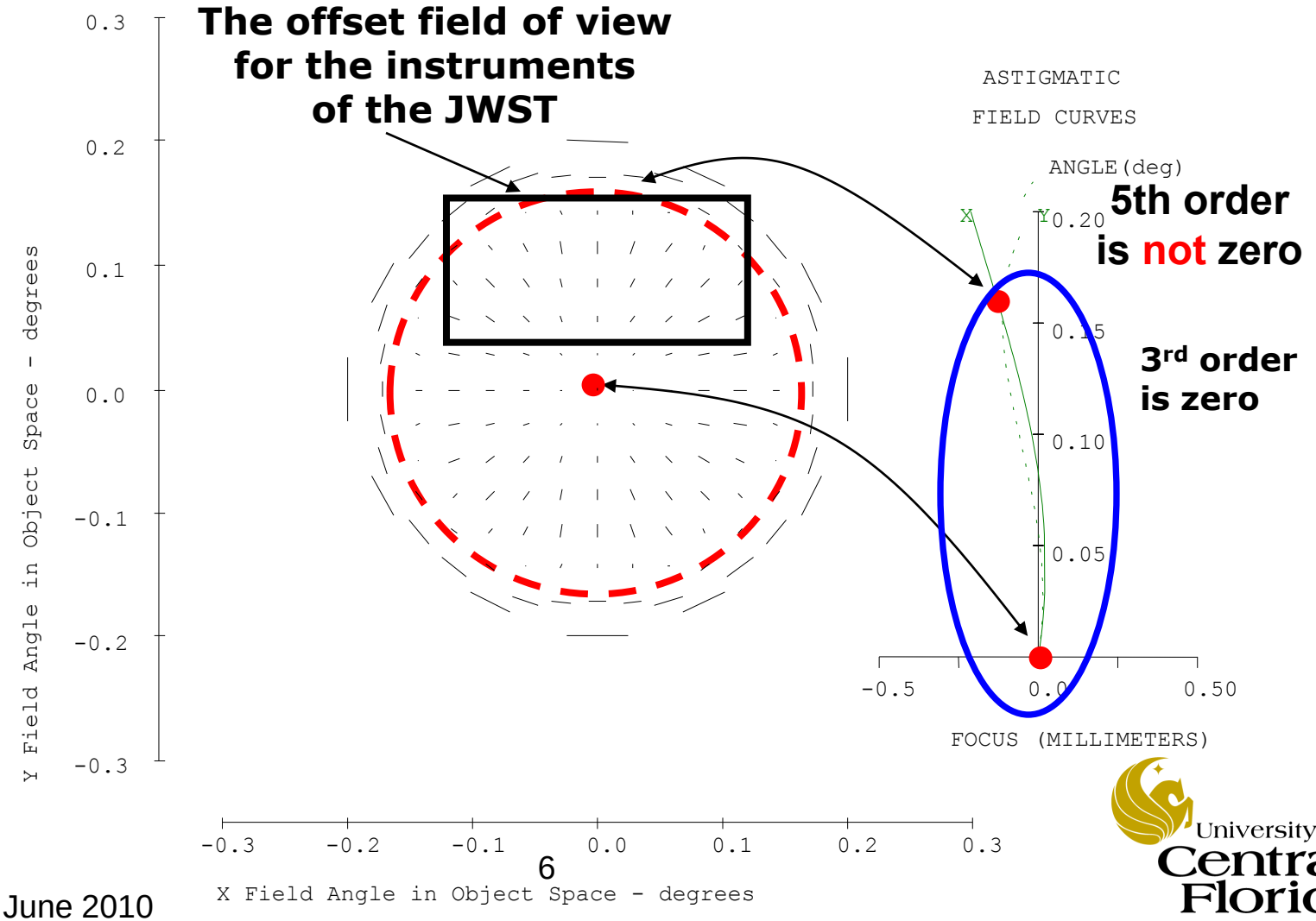
Overview
The JWST
Three Mirror Anastigmat (TMA)

- **The JWST is an obscured aperture, field-biased three-mirror telescope corrected for all third order aberrations, if aligned perfectly**
- **It has a 6.6M (segmented) aperture and a 0.33 degree Full FOV**
- **Like the Hubble Space Telescope, most of the instruments use portions of the field at the periphery of the field, making the overall system significantly more alignment sensitive**

JWST
A Field Bias, Obscured TMA

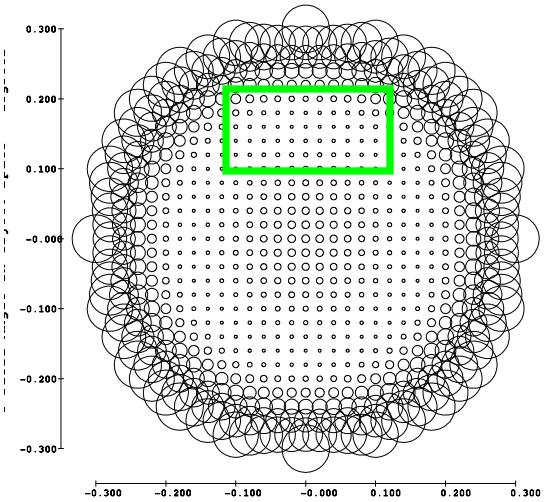


The JWST Telescope Field of View Limit 5th order Astigmatism

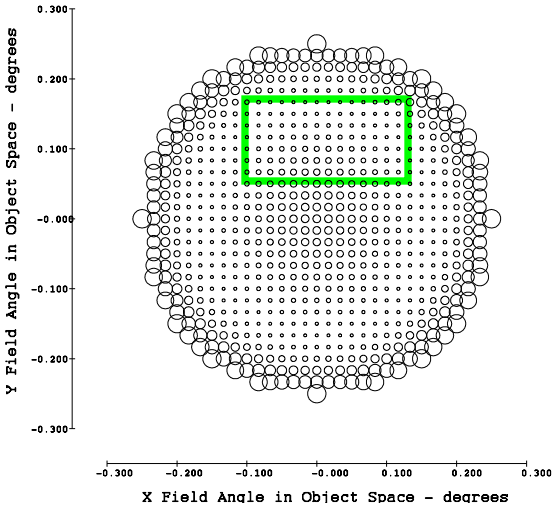


The High Order "Boundary"

Aligned
RMS Wavefront Error



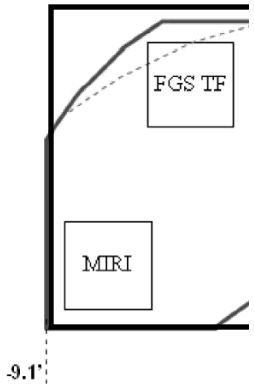
Aligned
RMS Wavefront Error

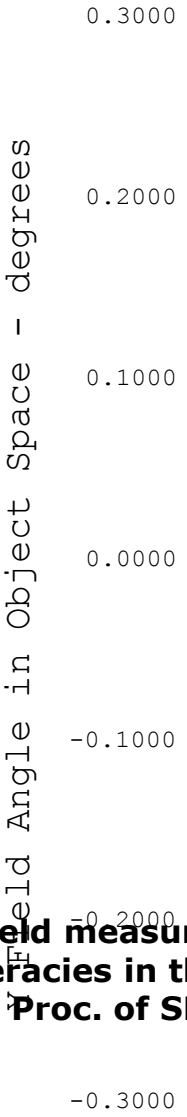


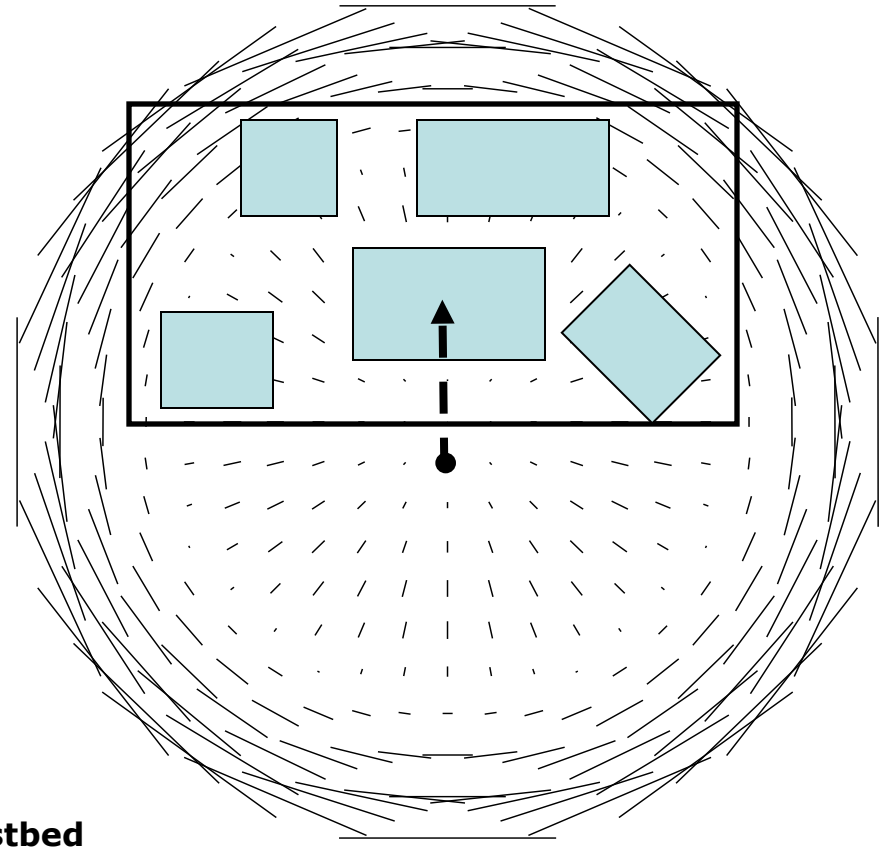
20% oversize to demonstrate
The "strength" of the
High order boundary

OPTICAL RESEARCH ASSOCIATES

ORAengineering



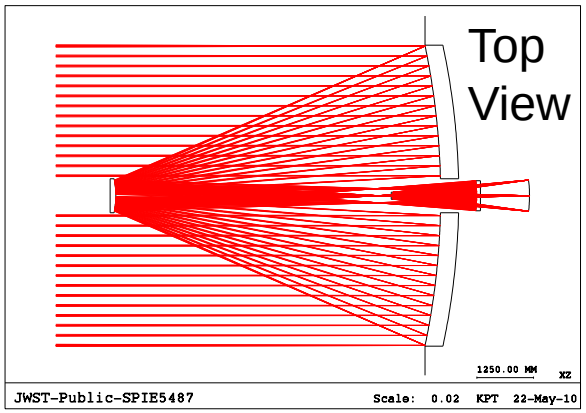


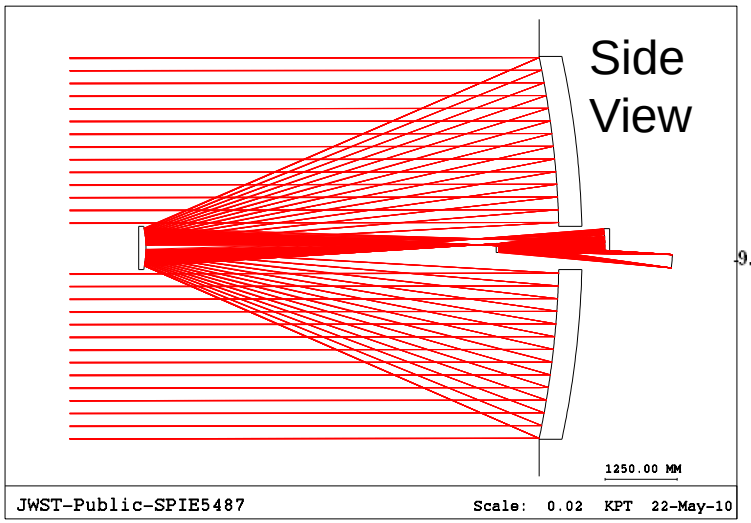


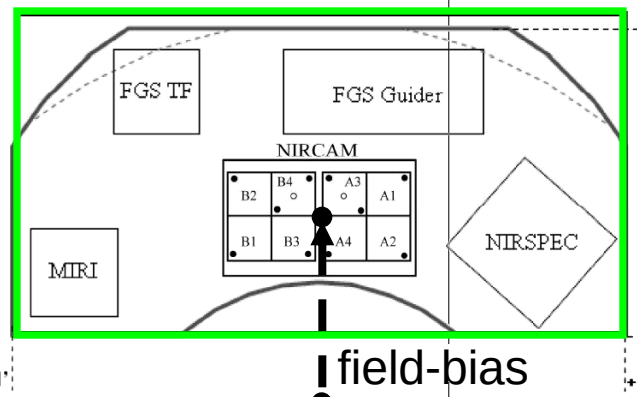
Erin Sabatke, "Using Multifield measurements to eliminate alignment degeneracies in the JWST Testbed Telescope," Ball Aerospace, Proc. of SPIE Vol. 6687 668707-1, 2007

Some instruments are themselves a series of TMAs, SPIE OPTIFAB 2009

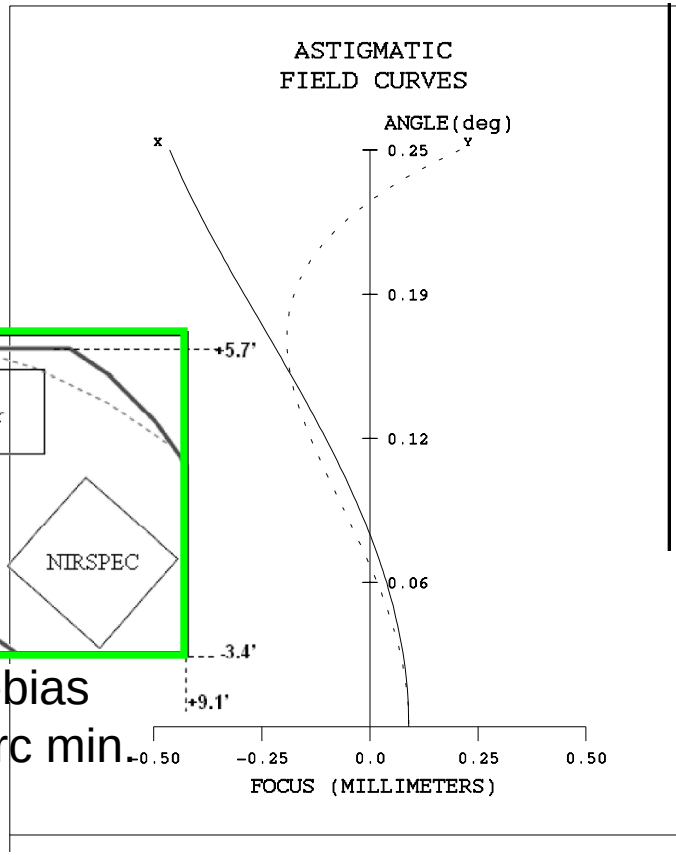
Overview of JWST FOV





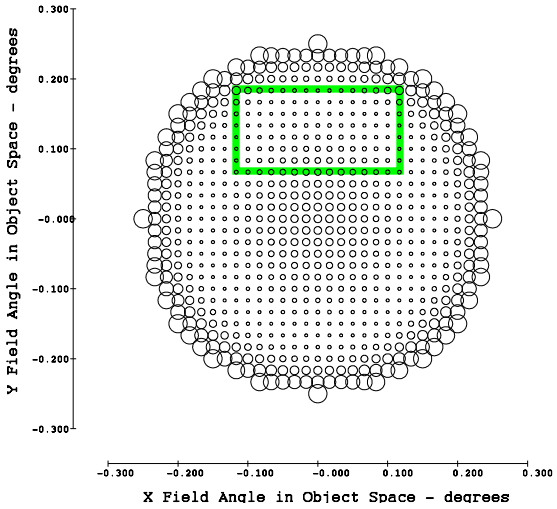


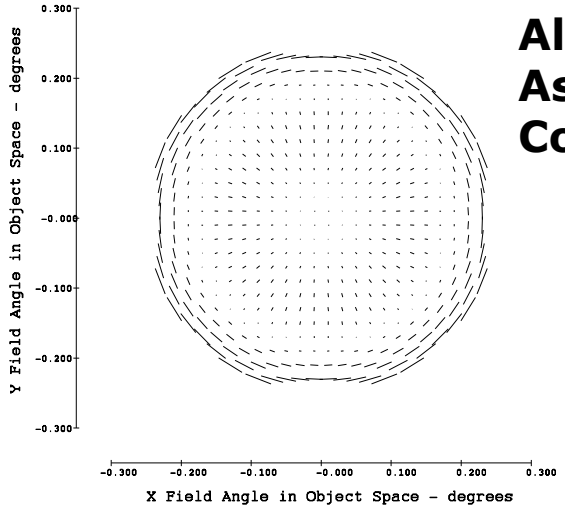
field-bias
~7 arc min.



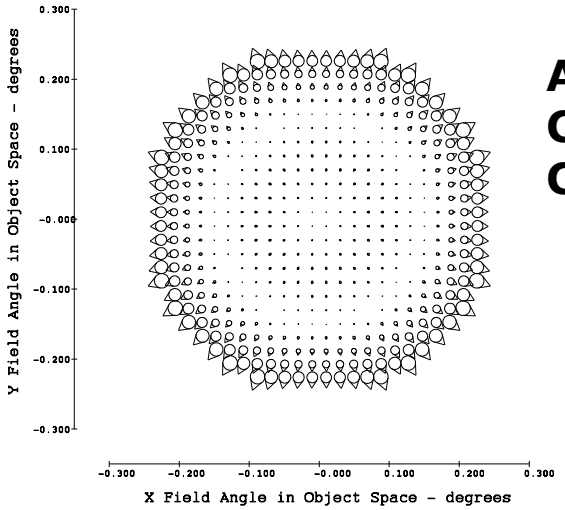
Real-Ray Zernike Based FFD Analysis Aligned JWST

Aligned RMS Wavefront Error





All Orders Astigmatic Component

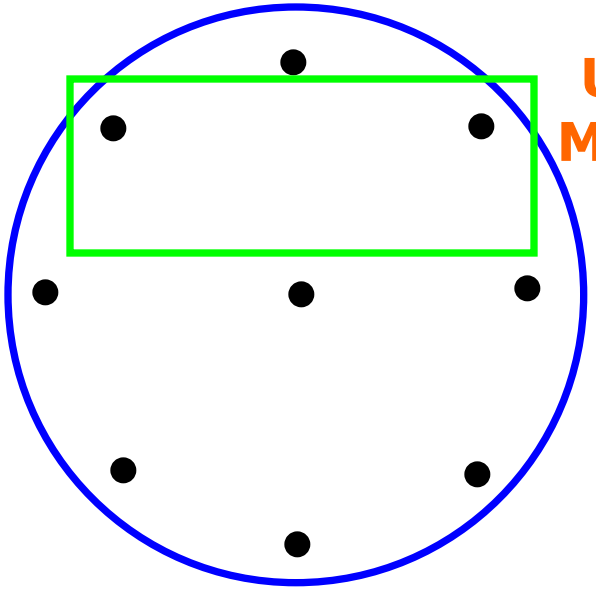


All Orders Comatic Component

No other Zernike Terms Are Significant

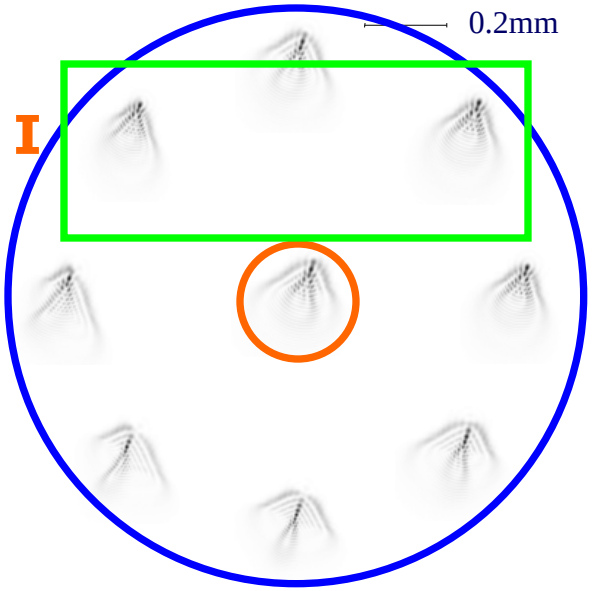
Misalignment-Induced JWST Aberrations 3rd Order Coma

TMA



Uncontrolled Misalignment I

TMA



Ideally Corrected

$$W = 0$$

Field-Constant 3rd Order Coma

$$W = (\boldsymbol{A}_{131} \cdot \boldsymbol{\rho})(\boldsymbol{\rho} \cdot \boldsymbol{\rho})$$

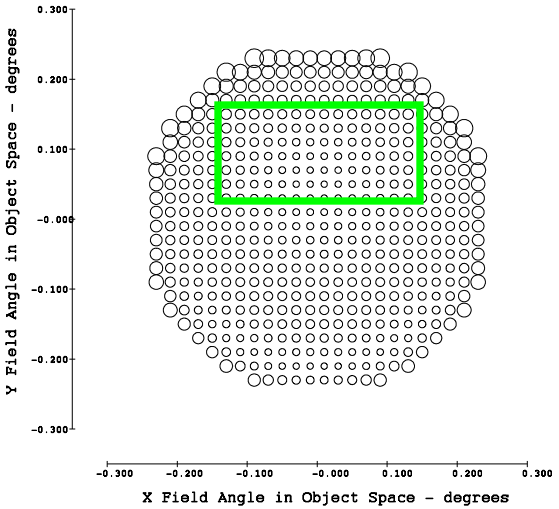
$$\sum_j W_{131_j} \boldsymbol{H} = W_{131} \boldsymbol{H} = 0$$

$$\boldsymbol{A}_{131} \equiv \sum_j W_{131_j} \boldsymbol{\sigma}_j$$

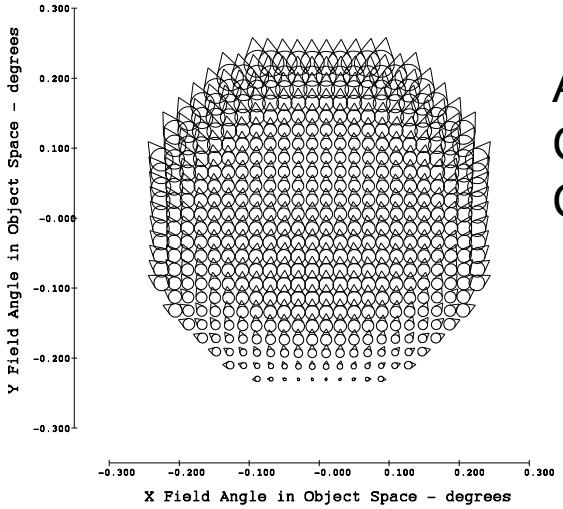
K. P. Thompson, T. Schmid, O. Cakmakci, and J.P. Rolland, "A real ray-based method for locating individual surface aberration field centers in imaging optical systems without symmetry," JOSA A 26, pp 1503-1517 (2009).

FFD Analysis Misalignment Coma

Decentered Component
RMS Wavefront Error



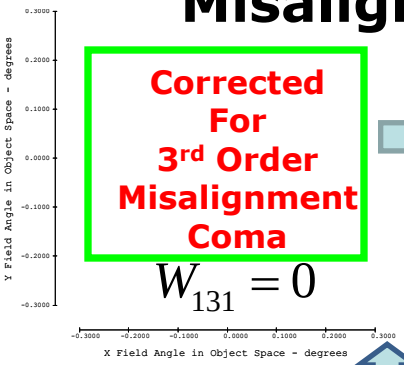
Change Dominated
by 3rd Order Field
Constant Coma



All Orders
Comatic
Component

Misalignment-Induced JWST Aberrations II
3rd Order Astigmatism

Misalign II

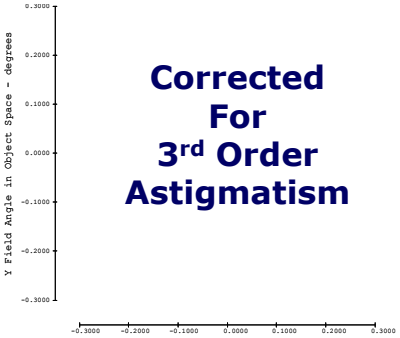


Corrected For 3rd Order Misalignment Coma

$$W_{131} = 0$$

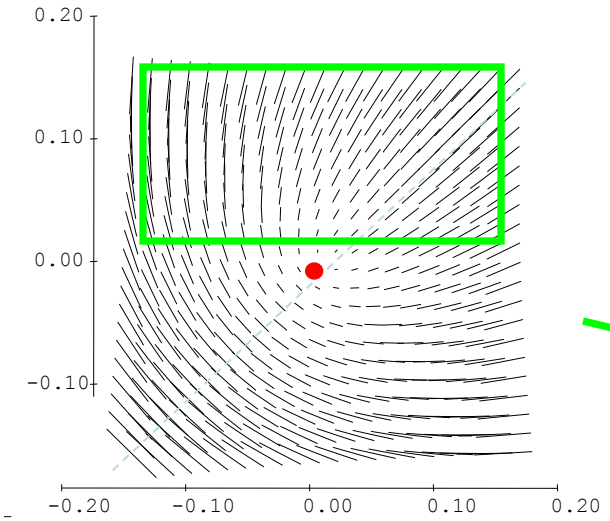
Misalign I

anastigmatic



Corrected For 3rd Order Astigmatism

Corrected for 3rd order astig.

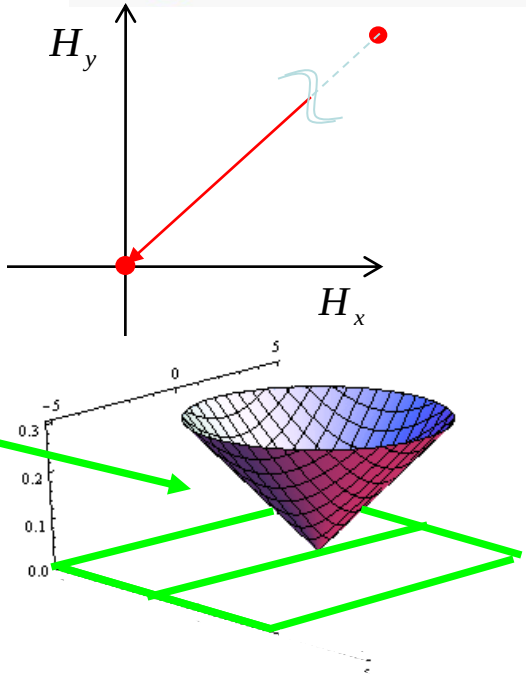


$$W = \frac{1}{2}[W_{222}\boldsymbol{H}^2 - 2\boldsymbol{A}_{222}\boldsymbol{H} + \boldsymbol{B}_{222}^2]\cdot\boldsymbol{\rho}^2$$

$$W_{222} \to 0 \quad \boldsymbol{B}_{222}^2 \to 0 \; misalignments \; small$$

$$W = -(\boldsymbol{A}_{222}\boldsymbol{H})\cdot\boldsymbol{\rho}^2$$

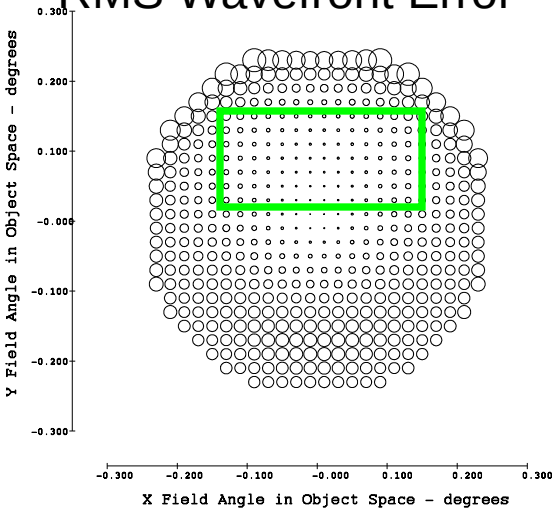
3rd order field-linear, field asymmetric astigmatism



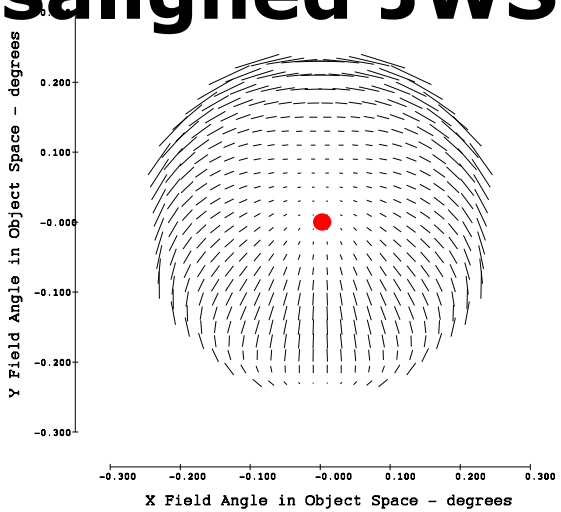
K. P. Thompson, T. Schmid, and J.P. Rolland, "The Misalignment induced aberrations of TMA telescopes," Optics Exp. 16 (25), pp 20345-20353 (2008).

FFD Analysis Coma-Free Pivot Misaligned JWST

No Figure Error
Misaligned Component
Coma-Free Pivot
RMS Wavefront Error

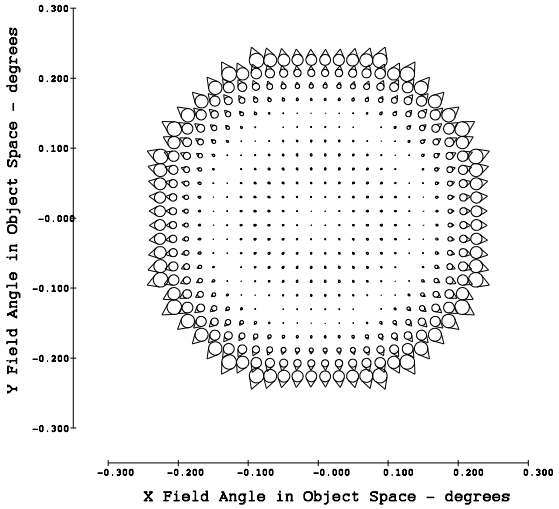


No Figure Error



Astigmatic
Component
Misalignment
Only

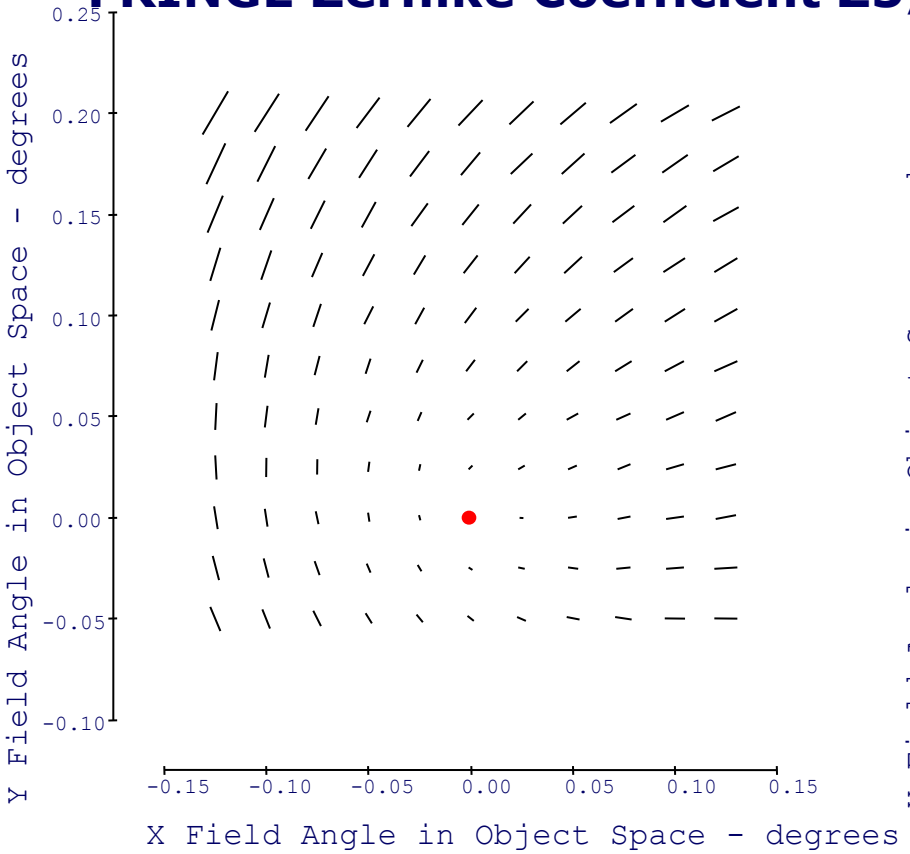
Change Dominated by
3rd Order Field-Linear,
Field-Asymmetric Astig.



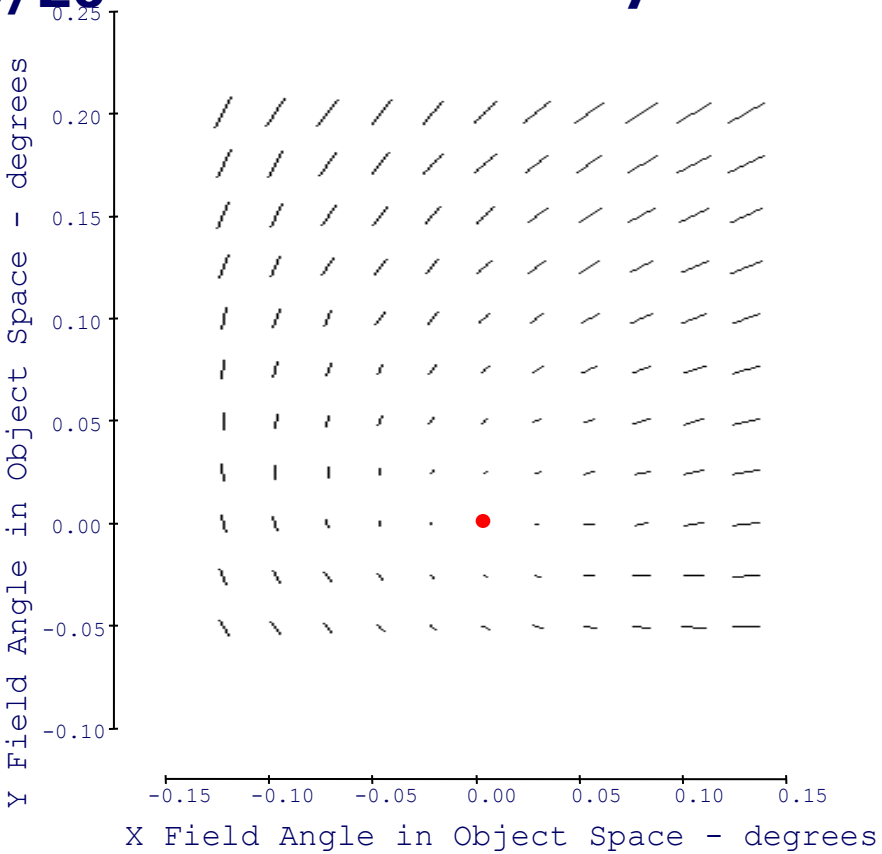
Comatic
Component
Coma-Free
Pivot

Real Ray vs. Theory
Field-Linear, Field Asymmetric
3rd Order Astigmatism

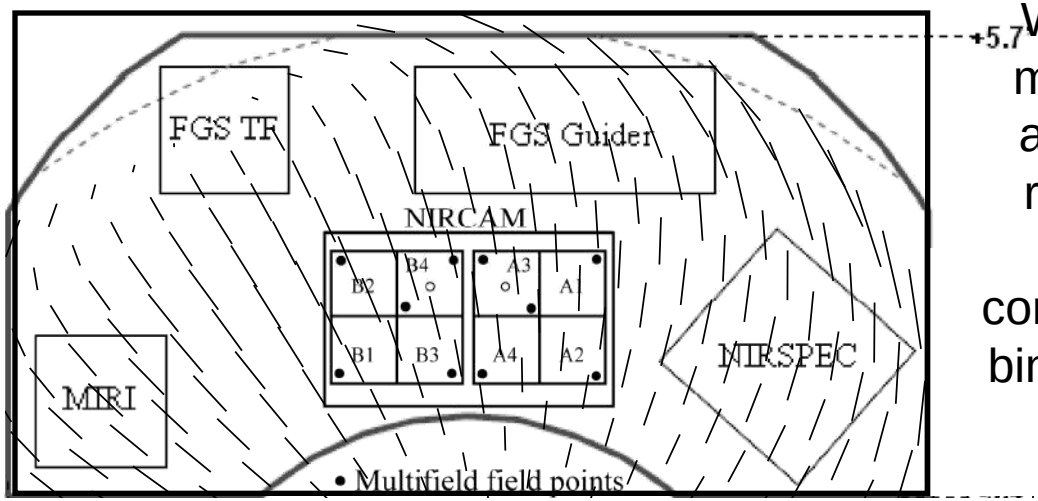
Real Ray Based
FRINGE Zernike Coefficient Z5/Z6



Predicted from
Nodal Theory



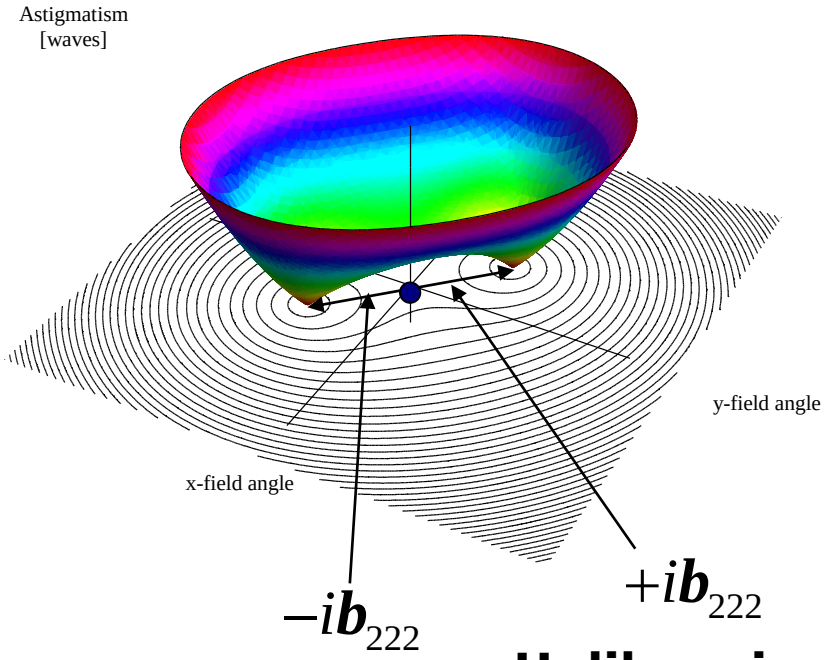
If There Were No Primary Mirror Figure Error



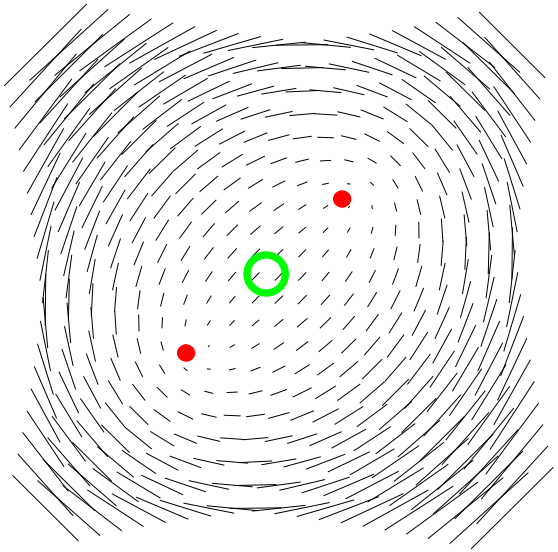
Without the insight of misalignment induced aberration theory, the rotation of astigmatic images can appear complex, they are simply binodal fields interacting with a boundary

Because the Phase Diversity measurements are made at the backend of instruments that are themselves complex, some with multiple TMAs, understanding the nodal signatures of the instruments, before their data is used to predict the state of the telescope would be leveraged as a basis to create a highly accurate analytic model for support during alignment

The Astigmatic Field with Primary Mirror "Figure Error"

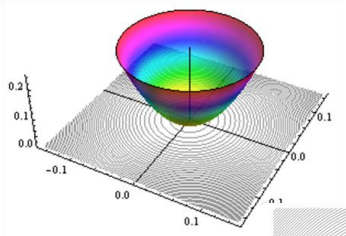


(a)

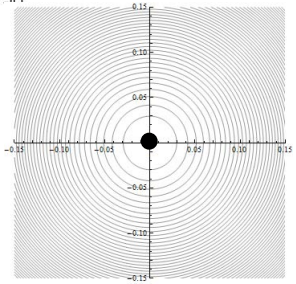


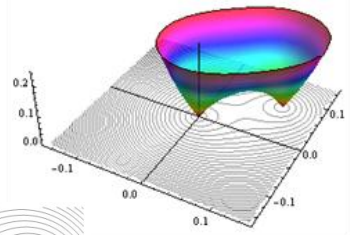
Unlike misalignment which create field-centered, field-linear, field-asymmetric astigmatism, primary mirror figure error creates field-centered, field-binodal, field-plane-symmetric astigmatism

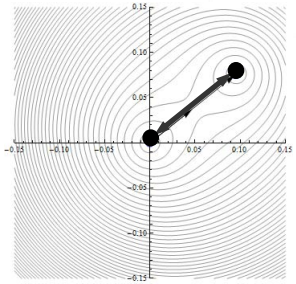
Astigmatic Nodal States of Coma-Aligned JWST Including Figure Error



Aligned And No Figure Error

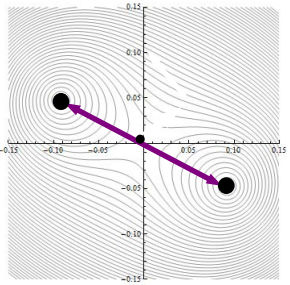


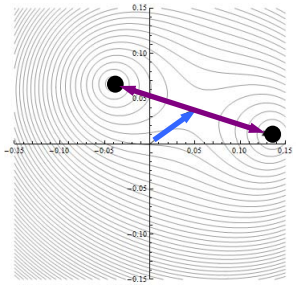




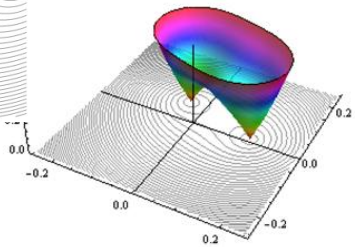
Misalignment But No Figure Error

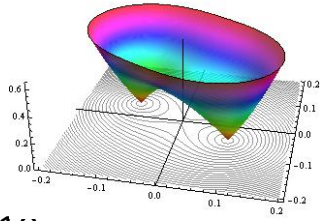
Aligned But With Figure Error





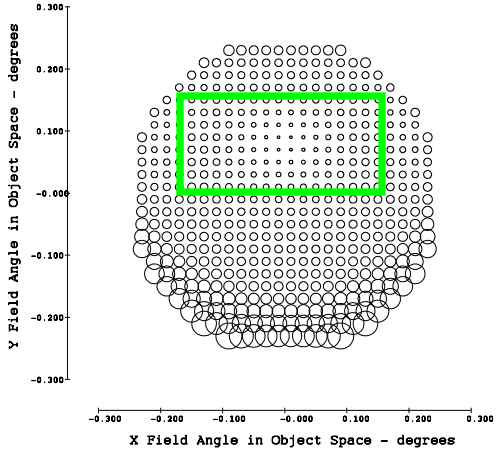
Misalignment And Figure Error

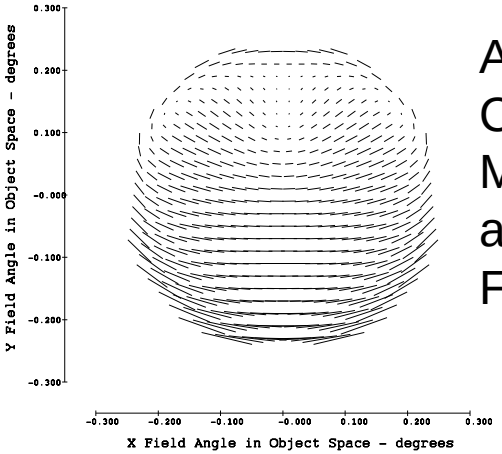




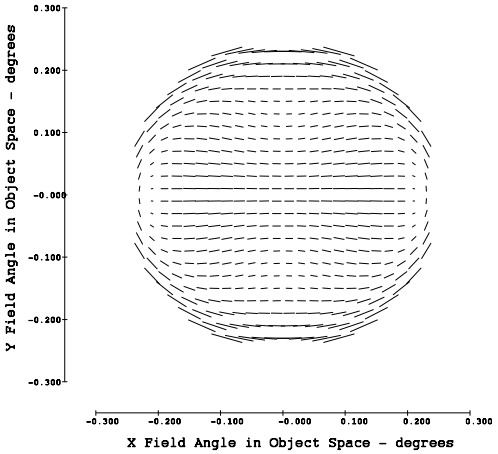
FFD Analysis Coma Corrected Misaligned JWST With Figure Error

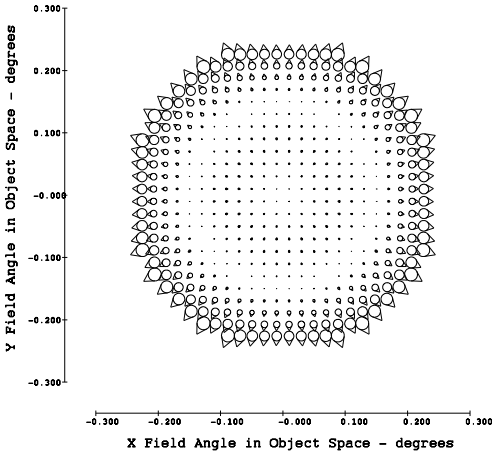
With Figure Error
Misaligned Component
Coma-Free Pivot
RMS Wavefront Error





Astigmatic
Component
Misalignment
and
Figure Error





Comatic
Component

Astigmatic Component Figure Error Only, Dominantly 3rd Order Field-Binodal Astig.

Conclusions
JWST Performance Limiting Misalignment Aberrations

- **It is considered important, and readily accomplished, to report the 3rd order misalignment aberration fields of the instruments to be used in collecting Phase Diversity data**

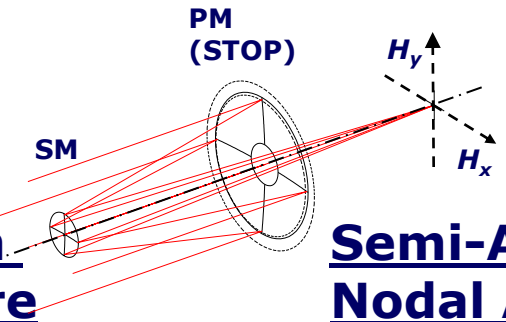
- **The aberrations to concentrate on at final alignment are**
  - **field-constant 3rd order coma**
  - **field-centered, field-linear, field-asymmetric 3rd order astigmatism**
  - **field-centered, field-binodal 3rd order astigmatism**

- **Separating the misalignment and figure error components makes best use of compensating dynamic range - Phase Diversity measurements from at least two and preferably three instruments allow distinguishing these two components**

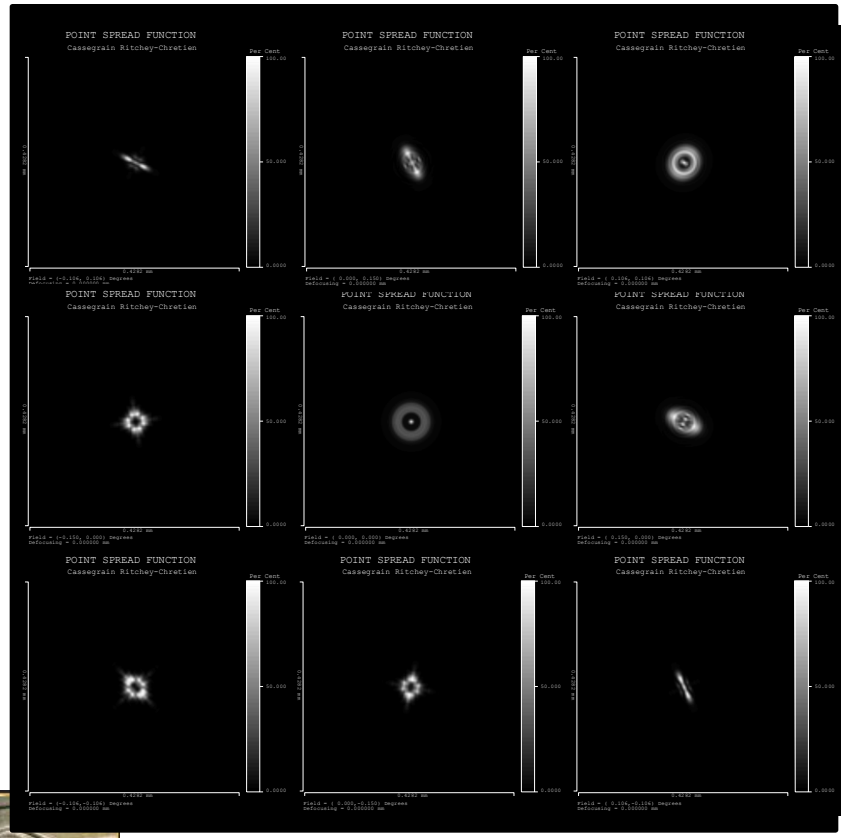
Acknowledgements

- This work was and is supported by,
  - the Florida I-4 Corridor program,
  - the University of Rochester,
  - Optical Research Associates

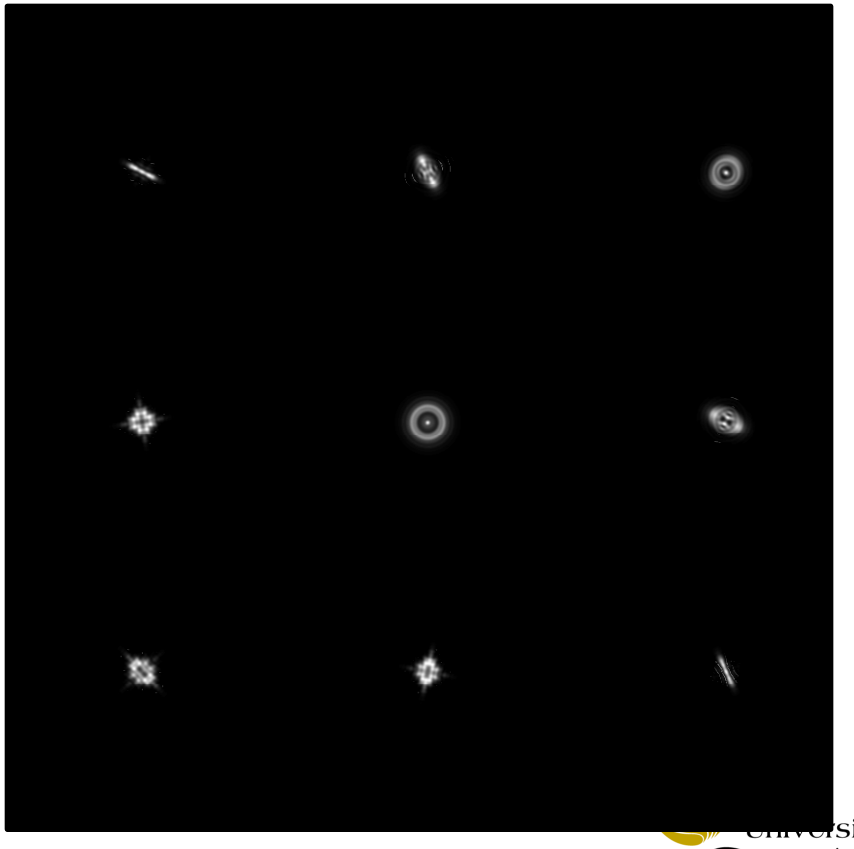
Recent Advances in Simulation



PSF computed with Raytracing Software



Semi-Analytical PSF utilizing Nodal Aberration Theory

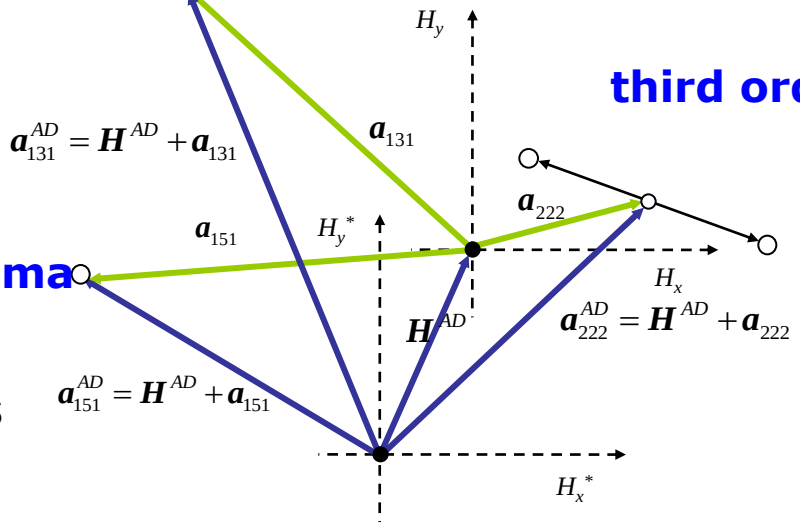


Application to the LSST is more complex
Alignment Strategy based on Z5/6, Z7/8, and Z14/15

third order coma

third order astigmatism

fifth order coma



Paper to be presented at SPIE Astronomy later this month

express dependence on misalignment parameters

$$\boldsymbol{a}_{131}^{AD} = \boldsymbol{a}_{131} + \boldsymbol{H}^{AD}$$

$$\boldsymbol{a}_{151}^{AD} = \boldsymbol{a}_{151} + \boldsymbol{H}^{AD}$$

$$\boldsymbol{a}_{222}^{AD} = \boldsymbol{a}_{222} + \boldsymbol{H}^{AD}$$

=0

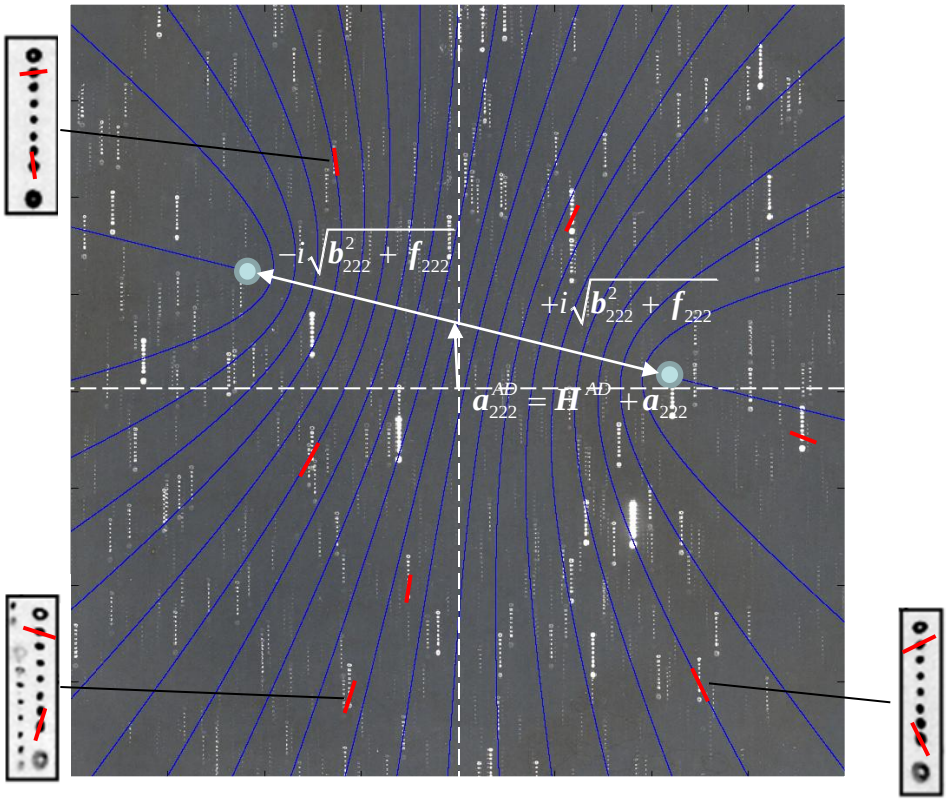
$$\boldsymbol{a}_{222} = \frac{1}{W_{222}}\left(W_{222,PM}^{(sph)}\boldsymbol{\sigma}_{PM}^{(sph)} + W_{222,PM}^{(asph)}\boldsymbol{\sigma}_{PM}^{(asph)} + W_{222,SM}^{(sph)}\boldsymbol{\sigma}_{SM}^{(sph)} + W_{222,SM}^{(asph)}\boldsymbol{\sigma}_{SM}^{(asph)} + W_{222,TM}^{(sph)}\boldsymbol{\sigma}_{TM}^{(sph)} + W_{222,TM}^{(asph)}\boldsymbol{\sigma}_{TM}^{(asph)}\right)$$

$$\boldsymbol{a}_{131} = \frac{1}{W_{131}}\left(W_{131,PM}^{(sph)}\boldsymbol{\sigma}_{PM}^{(sph)} + W_{131,PM}^{(asph)}\boldsymbol{\sigma}_{PM}^{(asph)} + W_{131,SM}^{(sph)}\boldsymbol{\sigma}_{SM}^{(sph)} + W_{131,SM}^{(asph)}\boldsymbol{\sigma}_{SM}^{(asph)} + W_{131,SM}^{(sph)}\boldsymbol{\sigma}_{SM}^{(sph)} + W_{131,SM}^{(asph)}\boldsymbol{\sigma}_{SM}^{(asph)}\right)$$

$$\boldsymbol{a}_{151} = \frac{1}{W_{151}}\left(W_{151,PM}^{(sph)}\boldsymbol{\sigma}_{PM}^{(sph)} + W_{151,PM}^{(asph)}\boldsymbol{\sigma}_{PM}^{(asph)} + W_{151,SM}^{(sph)}\boldsymbol{\sigma}_{SM}^{(sph)} + W_{151,SM}^{(asph)}\boldsymbol{\sigma}_{SM}^{(asph)} + W_{151,TM}^{(sph)}\boldsymbol{\sigma}_{TM}^{(sph)} + W_{151,TM}^{(asph)}\boldsymbol{\sigma}_{TM}^{(asph)}\right)$$

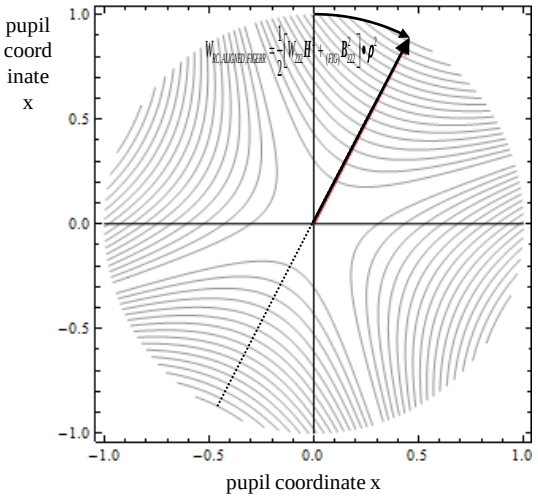
The First Evidence of MultiNodal Aberrations Through Focus Star Plates '77

- Astigmatic Nodes



Through focus photographic plate taken with the 90" telescope of the Steward observatory, located on Kitt Peak. This plate was taken in the 70's before the theoretical developments that led to nodal aberration theory and provided the first physical confirmation of the validity of this theory

Characterizing Figure Error as a Zernike Coefficient Interferogram



Primary Mirror Figure Error Characterized as C5/C6 Zernike Fit

$$W_{RC,ALIGNED,FIGERR} = \frac{1}{2}\left[W_{222}H^2 + {}_{(FIG)}B^2_{222}\right]\bullet\rho^2$$

$${}_{(FIGERR)}B^2_{222} \equiv 2\left({}_{(FIGERR)}C_{5,6}\right)\exp\left[j2\left({}_{(FIGERR)}\xi_{5,6}\right)\right]$$

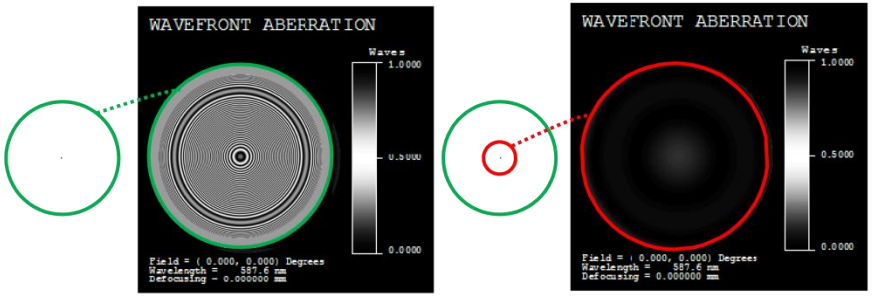
$${}_{(FIGERR)}C_{5,6} = \sqrt{\left({}_{(FIGERR)}C_5\right)^2 + \left({}_{(FIGERR)}C_6\right)^2}$$

$${}_{(FIGERR)}\xi_{5,6} = \frac{1}{2}ArcTan\left(\frac{-\left({}_{(FIGERR)}C_6\right)}{\left({}_{(FIGERR)}C_5\right)}\right)$$

T. Schmid, K.P. Thompson, and J.P. Rolland, "Separation of the effects of astigmatic figure error from misalignments using Nodal Aberration Theory (NAT)," submitted to Optics Express (May 2010)

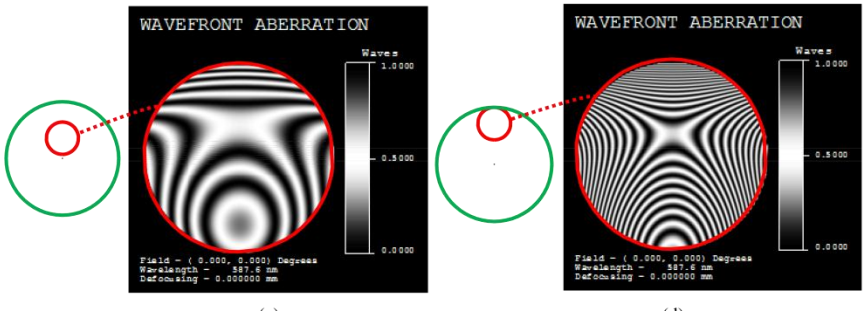
The "portal" for combining Zernike coefficient interferograms with nodal aberration theory

Full Aperture Aspheric Mirror **Spherical**



Centered Subaperture Nearly Null

Mild Offset Subaperture **Coma**



Strong Offset Subaperture **Astigmatism** And some coma

Offset aperture aspheres were included in the original nodal work in the 70s – this path can be exploited as a path to introduce mirror figure error, for mirrors at the aperture stop/pupils